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# CHARACTERIZING STELLAR PARAMETERS FROM HIGH RESOLUTION SPECTRA OF COLD/YOUNG STARS FOR SPIROU LEGACY SURVEY

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**Abstract.** We propose to create a high resolution spectral library in the optical and infrared range with PHOENIX model atmospheres code that can compute molecular lines in order to estimate stellar parameters. The chosen grid of stellar parameters will be as follows: $\delta T_{\rm eff}$ =25K, $\delta logg = 0.05$, $\delta[M/H] = 0.05$, ranging between: $T_{\rm eff} = [2500K, 4000K]$, $logg = [4.0, -5.5]$, $[M/H] = [-1, -1]$ but first, we need to calibrate on $F$ to $K$ stars. We present here the preliminary tests and calibration on the Sun and 18sco. The method yield respectively $T_{\rm eff} = 5770 \pm 3K$, $logg = 4.458 \pm 0.006$ and $T_{\rm eff} = 5763 \pm 3.5K$, $logg = 4.451 \pm 0.007$

Keywords: Stars, M dwarf, synthetic spectra, stellar parameters, PHOENIX

## 1 Introduction

Having well constrained stellar parameters is essential for deducing the properties of planets and magnetic fields from radial velocity and polarimetric data. Radiative transfer and stellar models are the key to analyze high resolution spectra in order to infer fundamental stellar parameters such as temperature, gravity, rotation, magnetic fields and composition. These initial results are necessary to analyze radial velocity and polarimetric data. The goal of this project is to construct, test and validate a high resolution synthetic spectral library using PHOENIX (Allard et al. 2011) model atmospheres with a reliable tool to estimate stellar parameters of M dwarfs. Directly fitting observed high resolution spectra to a library of synthetic ones can yield stellar parameters such as $T_{\rm eff}$, $logg$ and $[M/H]$, while enabling us to make a systematic error analysis. Valenti & Fischer (2005) have carried out a similar spectroscopic analysis for over a 1000 F to K type stars, deriving successfully parameters such as $T_{\rm eff}$, $logg$ and $[M/H]$ along with precise error estimates (44 K in $T_{\rm eff}$, 0.03 dex in $[M/H]$ and 0.06 in $logg$). Applying the same technique on M dwarfs is difficult and has not been done on a large scale yet. The spectral transition from F to M dwarfs requires a model atmosphere code that can treat molecular lines with accuracy such as PHOENIX. It is first necessary to create a new and finely-sampled spectral library with molecular lines using state-of-the-art stellar atmosphere models as well as to calibrate it to reproduce $F - G - K$ stars spectra. In this contribution we present some preliminary tests and calibration results for solar-like stars.

## 2 Synthetic spectra

We used the latest version of the model atmosphere code PHOENIX to synthesize stellar spectra. It is a three-step process : model atmosphere calculation, high resolution spectral synthesis and finally a continuum computation for normalization.

The model atmosphere is computed using existing "restart" files coming from old models (Allard et al. 2012). For each of our computed models, the restart file was carefully chosen to minimize the computing time to achieve convergence. The convergence criterion is defined as the difference (in %) between the total flux emitted and $\sigma T_{\rm eff}^4$ in each layer. Convergence is assumed when this criterion is lower than 1% in radiative layers. The models

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were calculated iteratively in spherical mode with 128 layers and assuming local thermodynamic equilibrium (LTE) until either convergence was achieved, or after $N$ iterations ($N = 20$).

Once the models were computed, they were used to produce high resolution spectra with micro-turbulent broadening and continua with PHOENIX. Allard et al. (2012) have conducted 2D radiative hydrodynamic model atmosphere simulations to estimate micro-turbulent motions as a function of $T_{\rm eff}$, which we used. As most of our observed spectra are flux normalized with the apparent continuum, it is necessary to have normalized synthetic spectra to compare against. PHOENIX can compute the actual continuum for a given set of stellar parameters. This is done by removing the discrete opacities, making any atomic and molecular data unavailable and by keeping dust and continuous opacities. As shown on Fig. 1, this yields a close to perfect continuum placement on the synthetic spectra.

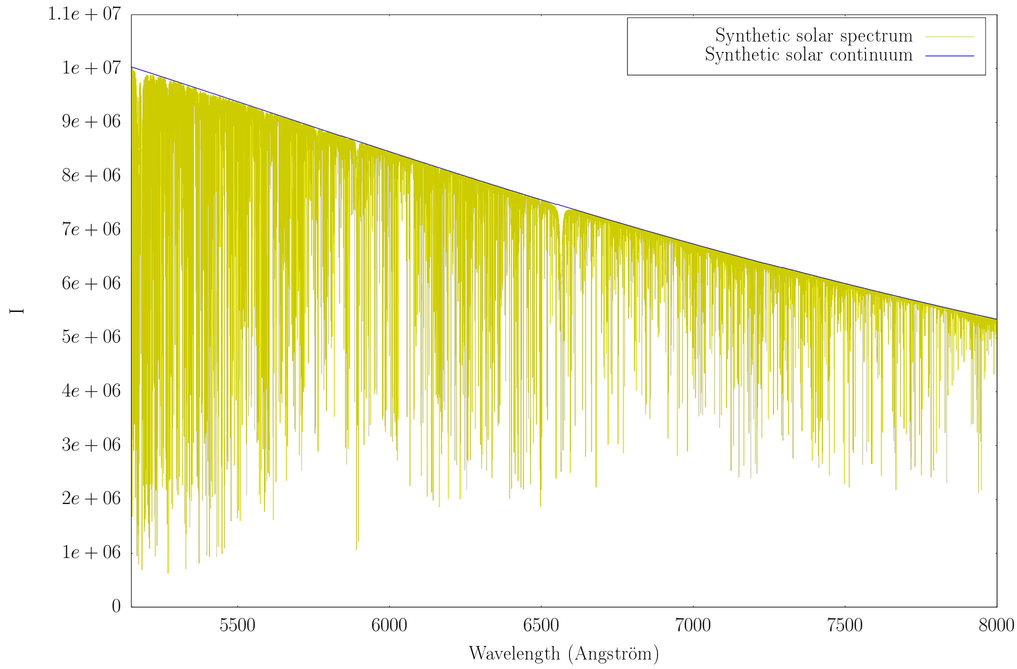


**Fig. 1.** Synthetic spectrum and continuum for the Sun ($T_{\rm eff} = 5775K$ and $logg = 4.440$)

## 3 Spectroscopic analysis tool

High resolution spectroscopy and stellar atmosphere modeling allow us to directly compare observed spectra to synthetic ones, across multiple spectral ranges in wavelength. This approach enables us to model all observed spectra uniformly and ensures self-consistency and statistical significance while estimating stellar parameters from a large sample of observed spectra.

Given a set of observations, estimating which model best fits the data is a well known problem in data modeling. The basic approach to solve this problem is generally to choose an estimator and a merit function that describes the agreement between the data and the model, and adjust the parameters of the latter to achieve close agreement. We used a maximum-likelihood estimator, also known as a $\chi^2$ estimator, and the Levenberg-Marquardt (LM) algorithm to search through the non-linear dependencies of the model parameters. For a given observed spectrum we compared it to a synthetic spectrum with known $T_{\rm eff}$, $logg$ and $[M/H]$ by fitting the following parameters directly using the LM algorithm: rotation velocity, radial velocity, macro-turbulence, and continuum coefficients. Given the fact that we are fitting different windows in wavelength, this function is computed window by window but fitted simultaneously to the observed spectrum. The resulting $\chi^2$ is used to map the parameter space in $T_{\rm eff}$, $logg$ and $[M/H]$ iteratively and estimate the optimum values.

## 4 Tests and validations

The first step of the test and validation consisted in creating a spectrum for the Sun in the optical range, as many high quality spectra have been collected with two spectropolarimeters, ESPaDOnS at CFHT and HARPS-Pol at ESO and for which high S/N high, high quality reduced spectra are available. We updated the existing PHOENIX atomic line data with the latest line data from the Vienna Atomic Line Database (Piskunov et al. 1995; Kupka et al. 1999, 2011). The database is dominated by line data from Kurucz & Bell (1995), but more recent results are incorporated periodically. We used the solar spectrum to determine empirical corrections for initial values of the oscillator strength that did not adequately reproduce observed line profiles, keeping stellar parameters fixed at known solar values. the oscillator strength of over 200 lines were corrected using the solar spectrum. We then used our spectroscopic analysis tool (SAT) to map the parameter space (keeping $[M/H] = 0$). Fig. 2 shows our results for the Sun, from which we find $T_{\rm eff} = 5770 \pm 3K$ and $logg = 4.458 \pm 0.006$. We then used SAT on a high S/N spectrum of 18 Sco (a solar analogue), on which our synthetic spectra were not calibrated, to also map the parameter space (by also keeping $[M/H] = 0$) and we obtained $T_{\rm eff} = 5763 \pm 3.5K$ and $logg = 4.451 \pm 0.007$. The latter results are in agreement with a similar analysis done by Valenti & Fischer (2005); they found $T_{\rm eff} = 5791 \pm 44K$ and $logg = 4.41 \pm 0.06$.

One should keep in mind that the given errors on the parameters are an estimate of the error bars using $\chi^2$ formal error analysis. This only gives us a lower limit for the error bars. This method never yields really good estimates of the error bars when the uncertainties are not independent and does not follow a normal distribution. In our case, uncertainties due to photon noise are completely dominated by systematic errors, which we are attempting to quantify.

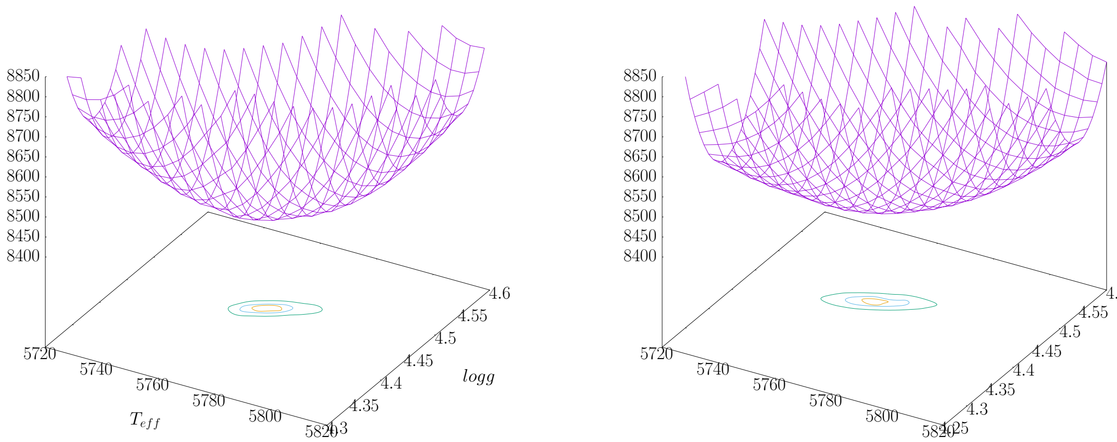


**Fig. 2. Left:** $\chi^2$ map for the Sun as a function of the $T_{\rm eff}$ and $logg$ with contours delimiting 68.3%, 95.4% and 99.99% of confidence level. **Right:** $\chi^2$ map for the 18 Sco as a function of the $T_{\rm eff}$ and $logg$ with contours delimiting 68.3%, 95.4% and 99.99% of confidence level .

## 5 Conclusions

Results from the first tests and validations are encouraging for the Sun and 18 Sco. Firstly, we need to extend these tests to other solar-like stars (similar $T_{\rm eff}$ and $[M/H]$) and confirm this performance as well as adding $[M/H]$ as an additional free parameter. Secondly, we need to extend our sample to a wider range of spectral types and validate the method on late G and early K type stars. The latter will probably require another empirical correction for initial values of the oscillator strength. A preliminary test on a sample spectrum from a K-type star suggested this will be necessary to once again anchor our models into standards. We also need to properly constrain the error bars on the parameters by estimating the uncertainties due to systematics.

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